Chapter 3 Background Geology

3.1 Geologic setting

There are numerous references that describe the geology of the region encompassing the Valle Vidal Unit, many of which are listed in Appendix 2 of this report. The most recent published paper on the resource potential of the region is by Hoffman and Brister (2003). Some of the discussions that follow are repeated, paraphrased, or expanded from that paper.

The eastern Valle Vidal Unit is located in the southern part of the Raton Basin, a Laramide geologic basin extending through southern Colorado and northern New Mexico (Fig. 3.1). From a physiographic perspective, this area is known as the Raton Mesa region, a highly stream-dissected, east-tilted mesa that marks the transition from the Sangre de Cristo Mountains of the Southern Rocky Mountains Province on the west, to the Great Plains Province on the east. The eastern edge of Raton Mesa in New Mexico is a prominent escarpment west of State Highway 64 between the towns of Raton and Cimarron. The western edge of the Raton Basin/Raton Mesa is essentially marked by two prominent hogbacks, locally known at the “The Wall” (westernmost) and “The Little Wall”/“Ash Mountain” (easternmost) where rock units that crop out in the eastern escarpment are tilted up against the Sangre de Cristo Mountains. From a coal mining perspective, the area is often referred to as the Raton Mesa coal area or region.

The eastern Valle Vidal Unit lies on the western edge of the Raton Basin/Raton Mesa region. The bedrock geologic unit at the surface in the Unit is the Poison Canyon Formation (Paleocene) that consists primarily of arkosic sandstone and conglomerate. The present topography of the Valle Vidal Unit (Fig. 1.1) is due to incision of modern stream valleys tributary to the Ponil and Vermejo Rivers into a planation surface (Pleistocene or older) that caps the hills and higher plateaus. Whitman Vega, the Beatty Lakes and other flat-floored valleys appear to have supported natural lakes during past wetter climates, but have for the most part since been captured and are drained by modern streams. The western margin of the eastern Valle Vidal Unit as addressed in this study is a north-northeast trending topographic ridge known as “The Rock Wall”, caused by differential erosion around a swarm of three erosion-resistant igneous dikes (Fig. 3.2). A similar prominent northeast-trending dike (“Firewall Dike”) forms another ridge informally named the “Firewall” (Fig. 3.3) that bisects the study area.

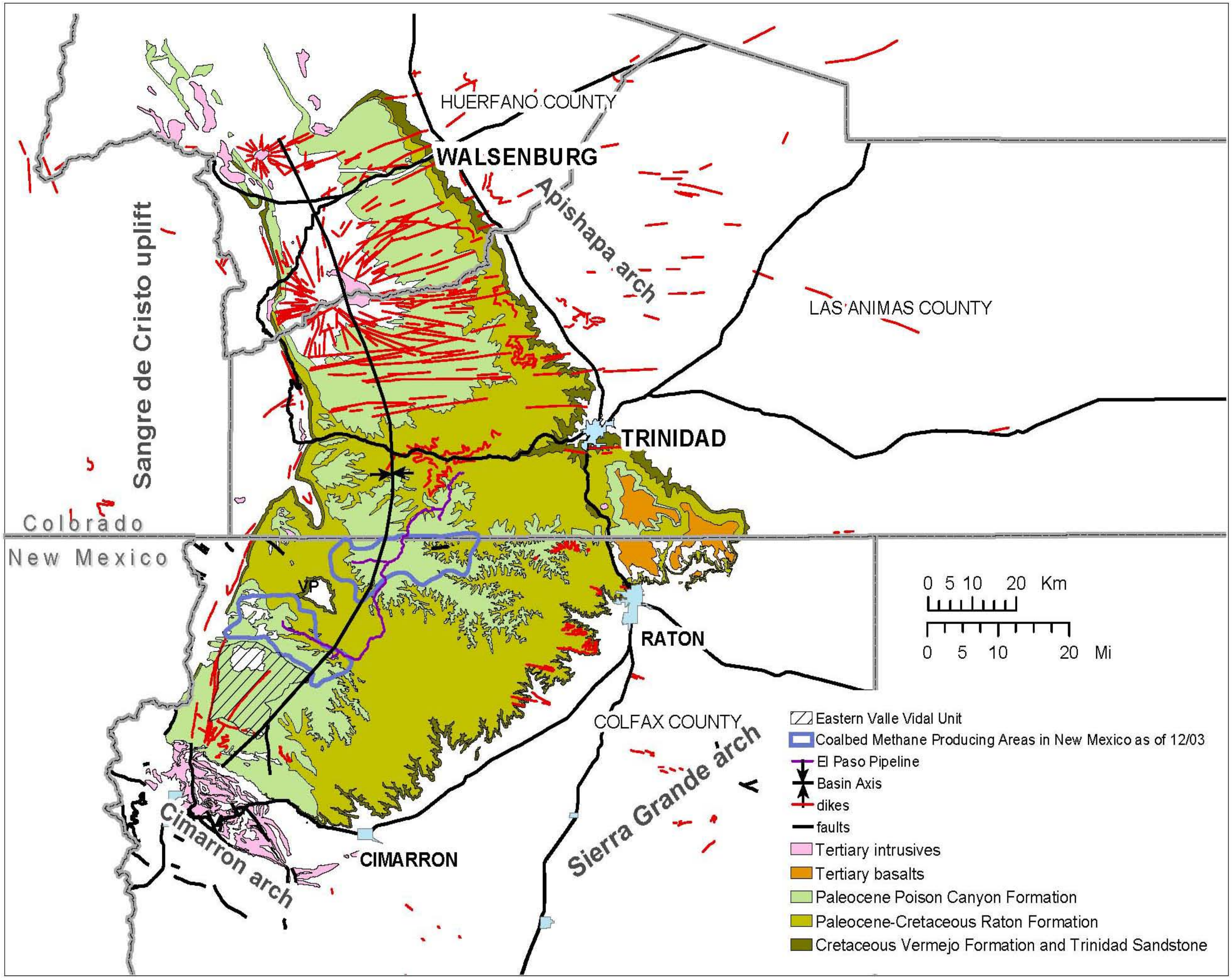


Figure 3.1 Geology and structural features of the Raton Basin, Colorado and New Mexico. Included are the eastern Valle Vidal Unit and coalbed methane-producing areas in New Mexico. VP = Vermejo Park. Geology derived from New Mexico Bureau of Geology and Mineral Resources (2003) and Tweto (1979). Figure modified from Hoffman and Brister (2003).

Figure 3.2 (top) Photograph taken from the vantage point of the Firewall dike near where it crosses North Ponil Creek looking westward. Three mountain ridges are visible in the photo including The Rock Wall, Ash Mountain, and Little Costilla Peak. Photo by Christopher Haley.

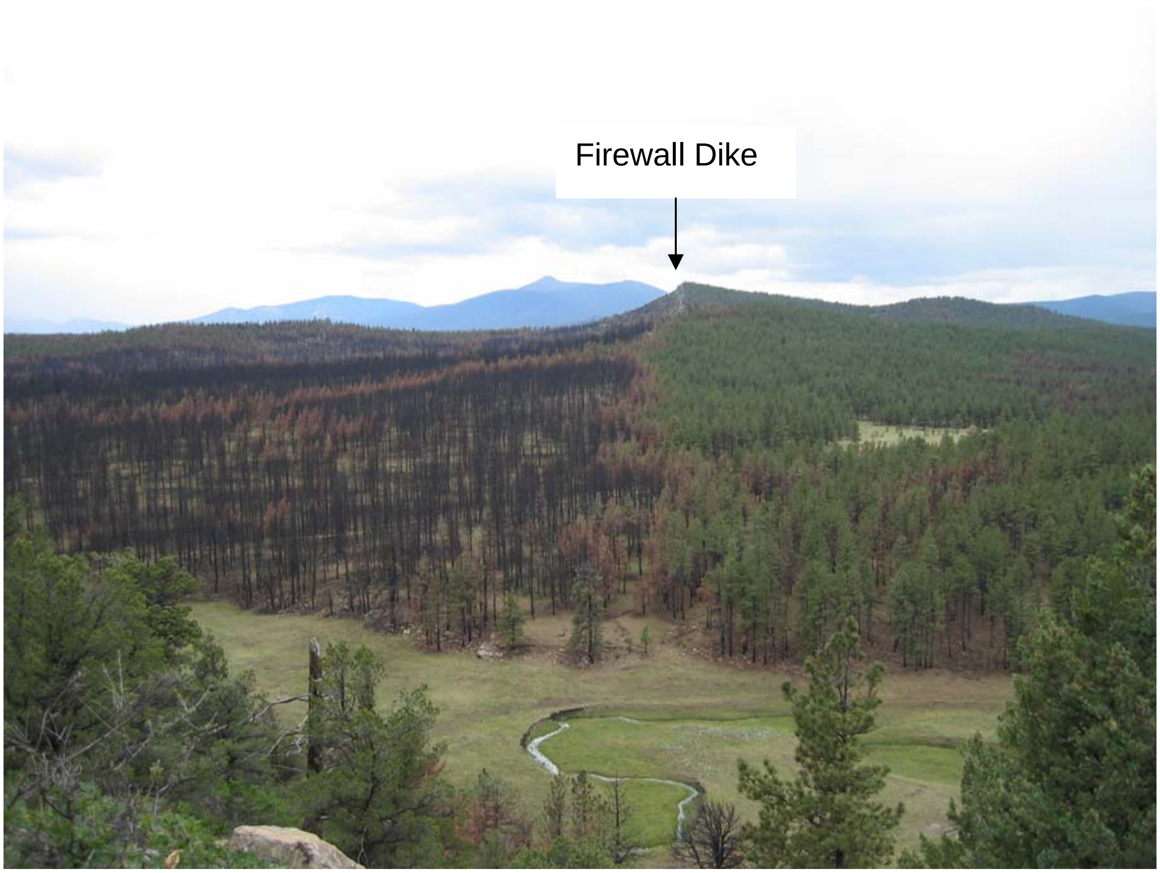


Figure 3.3 (bottom) Photograph taken from same vantage point of Figure 3.2 looking southwest along the Firewall dike. Note burned forest on the left and unburned trees on the right of the dike. Photo by Christopher Haley.

3.2 Structural geology

Baltz (1965) provided a thorough description of the Raton structural basin, paraphrased here. The Raton Basin is an elongate, slightly arc-shaped, northerly trending, asymmetric structural downwarp formed during the Laramide orogeny (Late Cretaceous to Eocene; Fig. 3.1). On its steeply dipping to overturned western flank lies the Sangre de Cristo uplift. Structural relief on Precambrian basement at the steep, western limb of the basin may be as much as 12,000-15,000 ft (Cather, 2004). To the north are the Wet Mountains uplift and Apishapa arch. The eastern flank dips gently (less than 3^o) westward from of the Sierra Grande arch. In New Mexico the post-Laramide Cimarron arch separates the basin into two subbasins, the southern of which was named the Las Vegas Basin by Darton (1928). The Upper Cretaceous to Paleocene coal-bearing Vermejo and Raton Formations of the Raton Basin exist only north of the Cimarron arch. Timing of basin formation is indicated by syndepositional structures in the Vermejo and Raton Formations (Lorenz et al., 2003) and an unconformity that places conglomeratic Paleocene Poison Canyon Formation in angular contact with older rocks at the basin's western and northern flanks (Baltz, 1965).

Cather (2004) describes multiphase Laramide development of the Raton Basin based on the stratigraphic record preserved there. The first phase is represented by the upper Pierre Shale (marine), Trinidad Sandstone (marginal marine-shoreface), and Vermejo Formation (non-marine) that document the regression of the Western Interior Seaway and progradation of sediments derived from the incipient Laramide Brazos-San Luis uplift, the eastern part of which is preserved as the Sangre de Cristo Mountains (Brister and Gries, 1994). The Raton and Poison Canyon Formations are, in part, lateral equivalents derived from the San Luis uplift and mark the medial phase of uplift and associated basin subsidence. The third phase is represented in Colorado by post-Poison Canyon formations. Subsidence of that phase may have been limited to the northern parts of the basin.

Figure 3.4 is a combined geologic and structure contour map of the top of the Trinidad Sandstone interpreted from a variety of data sources including oil and gas wells and published measured sections on the southern edge of the basin. The basin axis wraps around the eastern and southern flanks of the Vermejo Park (VP on maps) dome. It is important to emphasize that there are limited data points on which to base contour lines through the eastern Valle Vidal Unit. We anticipate that the estimated contour lines will move as additional well control points become available. The structure of the basin is an important factor in determining the oil and gas potential of the eastern Valle Vidal Unit. The influence of structure on each play type is discussed in Chapter 4.

It is notable that there is a general lack of faults shown on Raton Basin geologic maps. This may be due in part to the heavy vegetative cover of the region that obscures fault relationships. Numerous syndepositional faults are known to exist and have been documented in road cuts (e.g. Lorenz et al., 2003). The existence of fracture systems and their effects on reservoirs are well known (e.g. Stevens et al., 1992). There appear to be two sets of extensional fractures that have the potential to enhance permeability of reservoirs, with westerly and north-northeasterly azimuths (Scott Cooper, Sandia National Laboratories, 2003, pers. comm.).

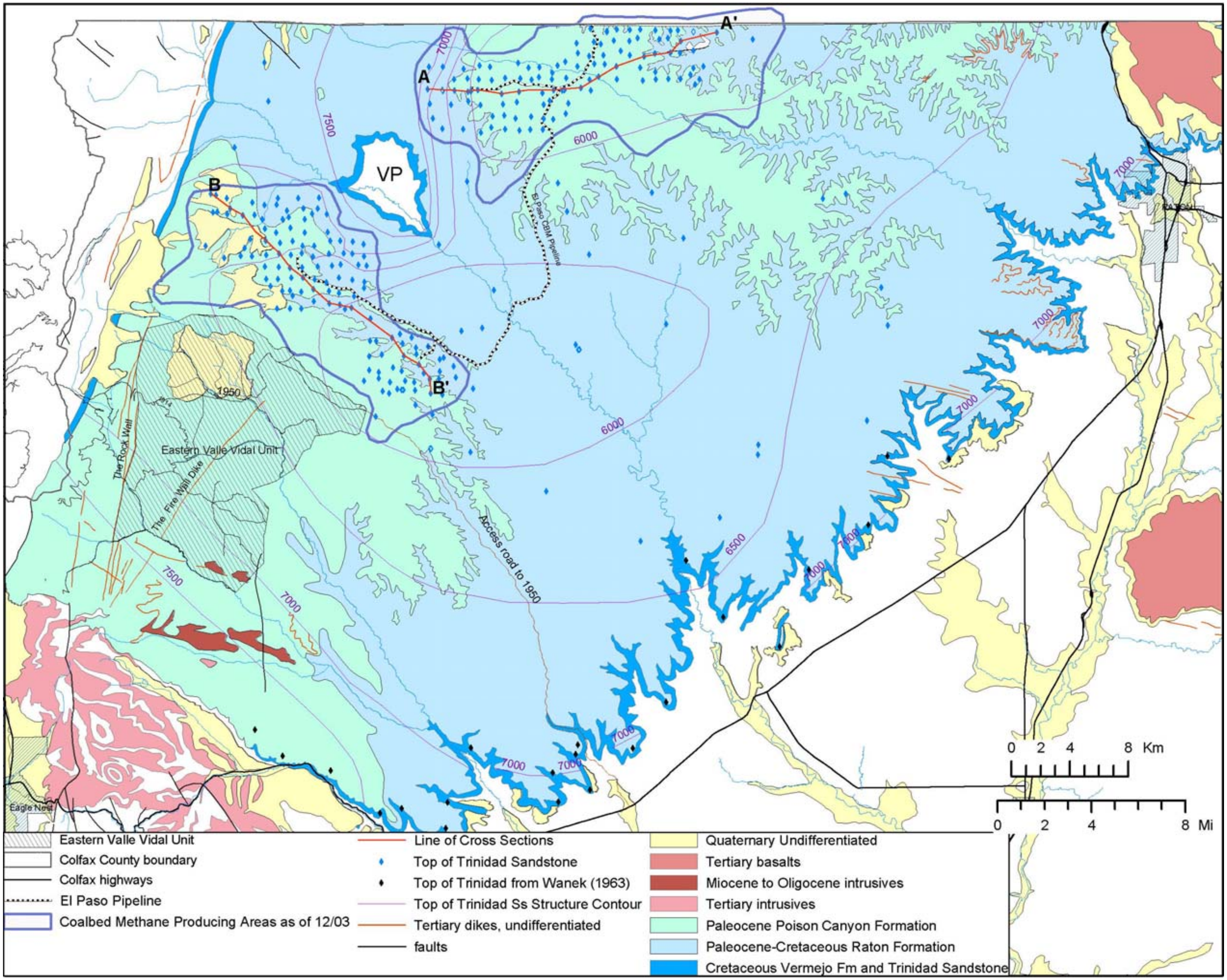


Figure 3.4 Structure-contour map of the top of the Trinidad Sandstone interpreted from well and surface data. VP = Vermejo Park. Contour interval = 500 ft. Modified from Hoffman and Brister (2003).

3.3 Stratigraphic summary

Figure 3.5 is a summary stratigraphic column for the eastern Valle Vidal Unit based upon Dolly and Meissner (1977) and Baltz and Myers (1999). It demonstrates the stratigraphic formations present, their general lithologies, oil and gas shows in the region, potential source rocks, and interpreted oil and gas plays. Figure 3.6 is a type lithology log and Figure 3.7 is a cross-section for the Unit.

Precambrian basement: Proterozoic supracrustal rocks in northern New Mexico include metavolcanic, metasedimentary and plutonic rocks ranging from 1765 to 1650 Ma, and granitic rocks ranging from 1500-1400 Ma (Williams, 1990). In the vicinity of the Valle Vidal Unit, Grambling and Dallmeyer (1990) describe the Proterozoic rocks outcropping in the Cimarron Mountains to the south, and Smith (1988) and Grambling et al. (1989) describe these rocks in the Taos Range to the west. Such rocks have no potential for generating oil and gas and very low potential for being fractured reservoirs of oil and gas. The Precambrian basement is capped by unconformities and may be overlain by Pennsylvanian or Permian rocks beneath the Valle Vidal Unit.

Pennsylvanian strata: Pennsylvanian shale and siltstone sediments may overlie Precambrian basement beneath the eastern Valle Vidal Unit. This assumption is based on early work by Shaw (1956) and later workers that suggest Pre-Pennsylvanian Paleozoic formations were likely eroded from the region prior to deposition of the Sandia Formation (Morrowan-Atokan) as a consequence of Mississippian initiation of uplift (De Voto, 1980) of the Ancestral Rockies.

The Sierra Grande-Apishapa uplift, an element of the Ancestral Rocky Mountains, was an emerging highland during the Pennsylvanian and early Permian (Fig 3.8). Detritus was shed westward into the subsiding intermontane Central Colorado trough, a basin bounded on the west by a southeastern extension of the Uncompaghre uplift (Mallory, 1972a; De Voto, 1980). It is possible, but unknown whether the Central Colorado trough was connected southwestward to the Taos trough and Rowe-Mora basin exposed today in the southern Sangre de Cristo Mountains.

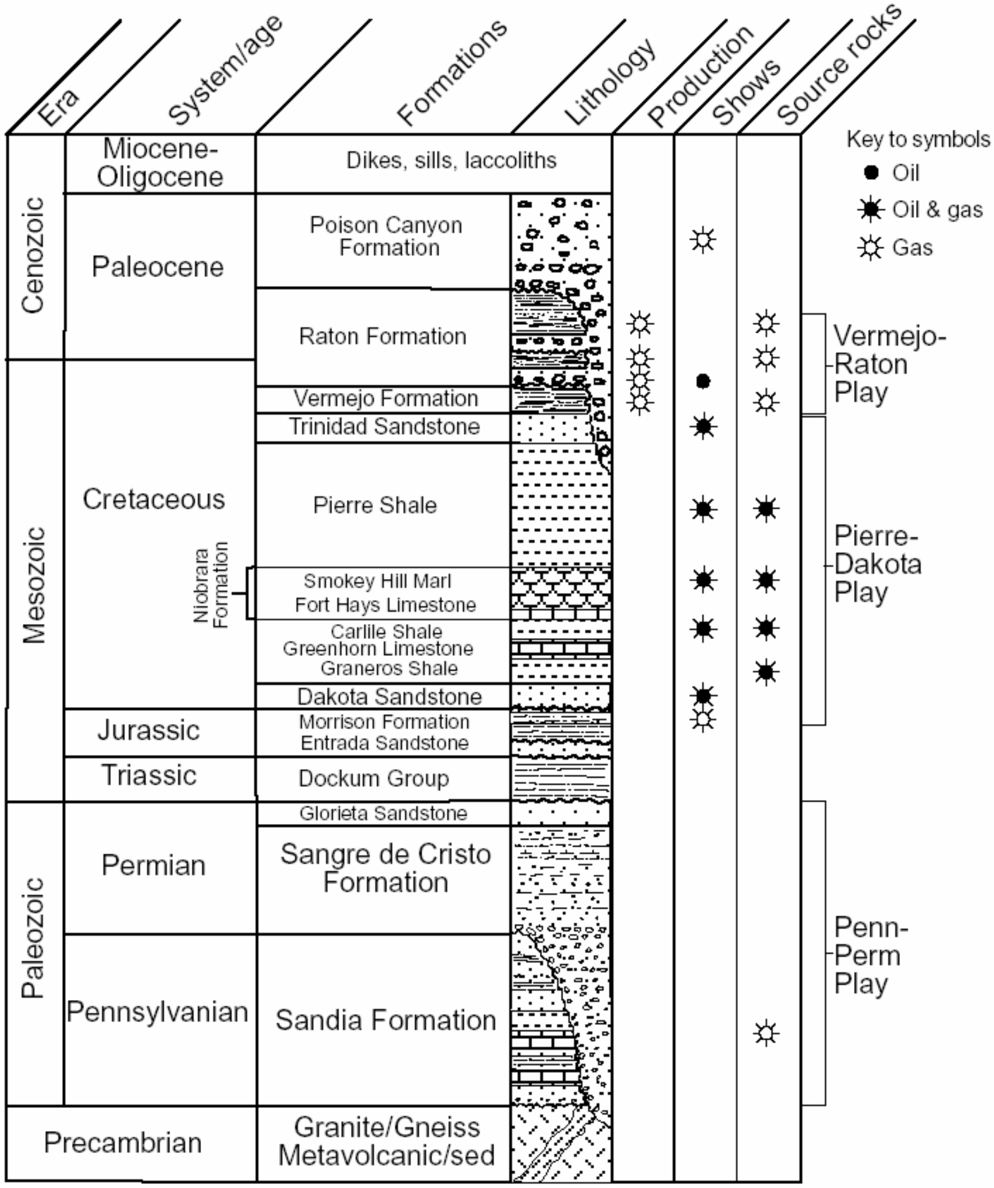
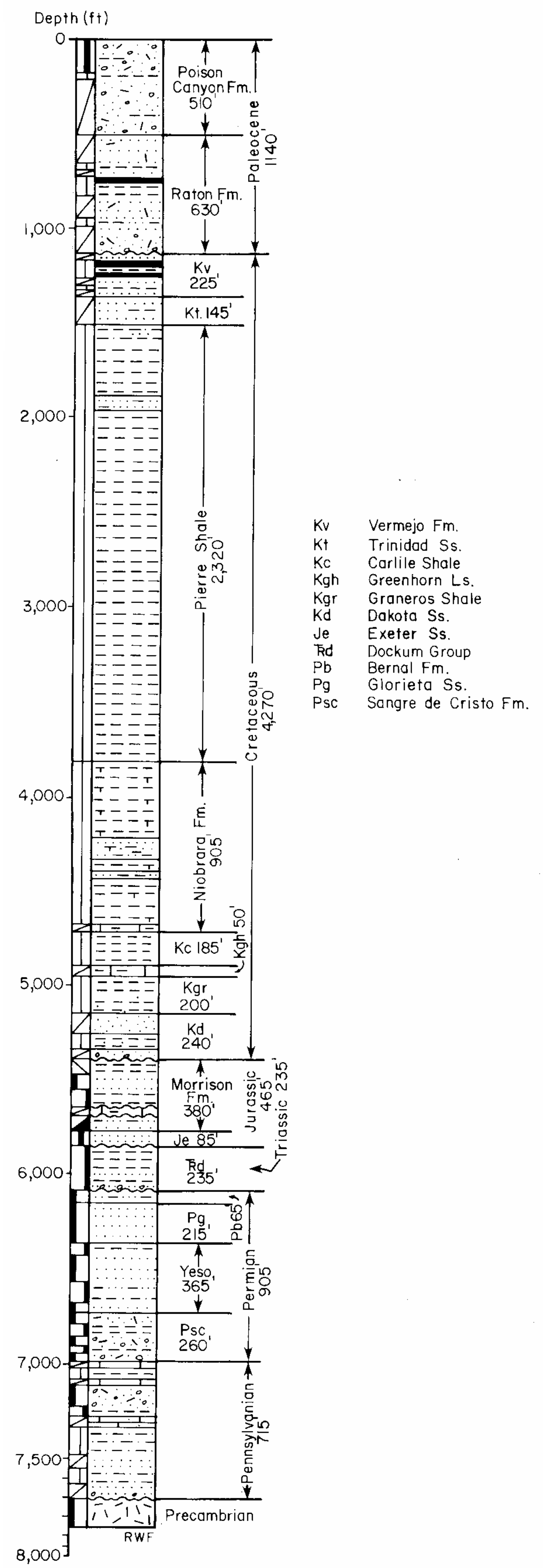


Figure 3.5 Generalized stratigraphic column for the New Mexico portion of the Raton Basin. Modified from Dolly and Meissner (1977).

Figure 3.6 Composite stratigraphic section, vicinity of eastern Valle Vidal Unit, Raton Basin, Colfax County, New Mexico. Surface to Triassic: Gourley No. 1 Vermejo Park, sec. 27, T31N, R17E. Triassic to Precambrian: Continental No. 2 St. Louis, Rocky Mountain, and Pacific, sec. 26, T31N, R21E. From Grant and Foster (1989). See original text for description of units



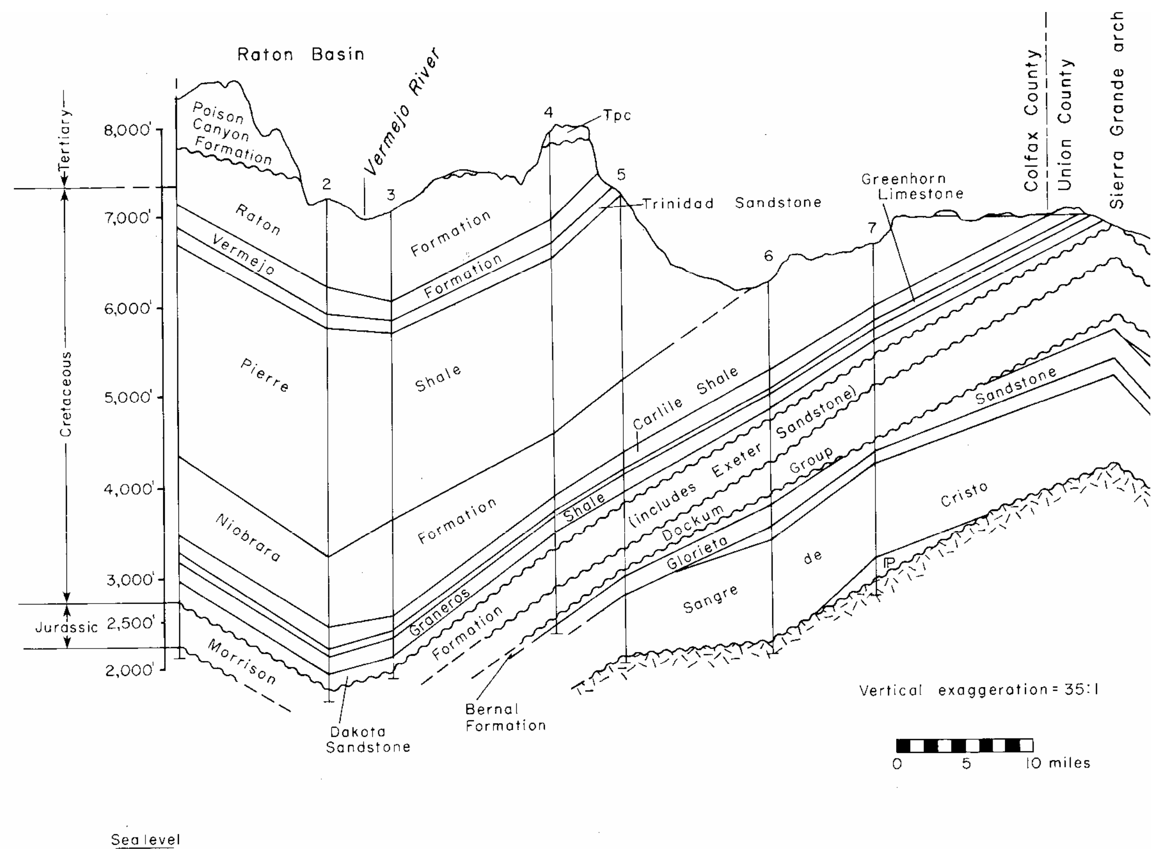


Figure 3.7 West-east cross section, Raton Basin, New Mexico. From Grant and Foster (1989).
Wells:

1) Gourley 1 Vermejo Park, Sec. 27, T. 31N., R. 17 E.
2) Gourley 2 Vermejo Park, Sec. 16, T. 30N, R. 19 E.
3) Odessa 2 W. S. Ranch, Sec. 30, T. 30 N., R. 20 E.
4) Conoco 3 St. Louis, Sec. 18, T. 30 N., R. 22 E.
5) Conoco 1 St. Louis, Sec. 24, T. 30 N., R. 22 E.
6) Condron 1 Moore, Sec. 10, T. 29N., R. 24 E.
7) HNG 1 Roach, Sec. 1, T. 29 N., R. 25 E.

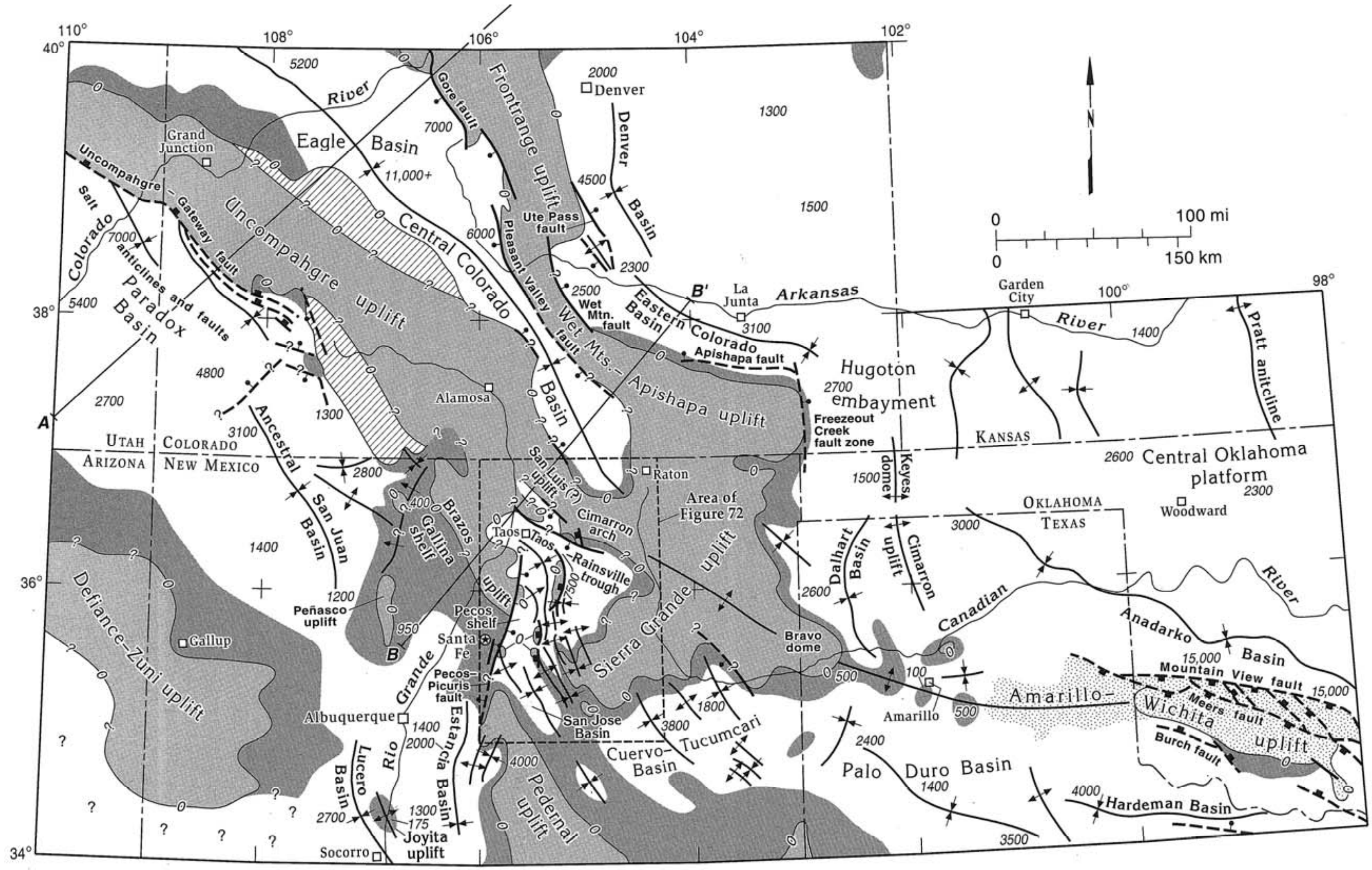


Figure 3.8 Principal late Paleozoic tectonic features of southern Colorado, northern New Mexico, and adjacent parts of Texas and Oklahoma. From Baltz and Myers (1999).

In their memoir on the Paleozoic rocks of the region, Baltz and Myers (1999) described the Sandia Formation as interbedded gray shale, carbonaceous shale, fine- to coarse-grained sandstone and conglomerate, and thin limestone. Minor coal seams were also noted. Gray and carbonaceous shales, and coal, are possible source rock lithologies, whereas sandstones could be reservoir lithologies. Grant and Foster (1989) allow for some potential for stratigraphic and structural traps in the Pennsylvanian in the western Raton Basin. Foster (1966) describes rocks similar to the Sandia Formation in the Conoco #2 Rocky Mountain well (listed in Oil and Gas Well Database on accompanying CD-ROM) drilled northeast of the Valle Vidal Unit by Conoco. No shows were reported for those rocks in that well.

Permian strata: Subsidence of the Central Colorado trough continued into the Permian as evidenced by the continued deposition of the conglomeratic upper Sangre de Cristo Formation (Wolfcampian) which eventually lapped eastward onto the Sierra Grande uplift. As the Ancestral Rocky Mountain orogenic event drew to a close, the subdued topography was onlapped by the Yeso Formation in some places, then capped by the marine Glorieta Sandstone (Leonardian). The Glorieta Sandstone is a medium grained, well-sorted sandstone. It is one of the deep saline aquifers used as a disposal zone for produced waters from coalbed methane operations on the Vermejo Park Ranch near the Valle Vidal Unit (Roy Johnson, NMOCD, 2004, pers. comm.). The Glorieta Sandstone is a potential reservoir at the top of the Pennsylvanian-Permian clastic pile. However, no shows of oil and gas have been reported.

Triassic and Jurassic strata: According to Grant and Foster (1989), The Triassic Dockum Group redbeds overlies the Permian strata with an unconformable contact. The eolian Entrada Sandstone, otherwise known locally as the Exeter Sandstone, in turn unconformably overlies the Triassic. The Morrison Formation redbeds cap the Entrada Sandstone, also with an unconformable contact. These formations lack source rock potential and have generally not yielded shows of oil or gas. At the Vermejo Park Ranch, the Entrada Sandstone is used as a disposal zone for produced water (Roy Johnson, NMOCD, 2003, pers. comm.). The upper Morrison Formation yielded a gas show of unknown quality while drilling a produced water disposal well on the Vermejo Park Ranch (Roy Johnson, NMOCD, 2004, pers. comm.), but the show apparently has not been confirmed by commercial production.

Dakota Sandstone through Pierre Shale (Cretaceous): The Lower to Middle Cretaceous Dakota Group (a.k.a. Dakota Sandstone) was deposited upon an unconformable surface. Its lower half is the deltaic Mesa Rica Formation (Albian; Lucas et al., 1998) or Purgatoire Formation (Baltz, 1965), whereas the upper half is the Romeroville Sandstone (Cenomanian; Lucas et al., 1998), a shallow marine/shoreface unit. The basal unit represents an unconformity-bounded transgressive event whereas the upper part is the base of a better-represented transgressive event in the region that includes the marine Graneros

Shale and is capped by the Greenhorn Limestone. These transgressions mark the advance of the Cretaceous Interior Seaway that eventually covered northern New Mexico. Baltz (1965) described the Dakota Sandstone as nearly all sandstone with lenses of conglomerate in outcrops on the western margin of the Raton Basin. The upper part of the Dakota grades into the marine rocks of the overlying Graneros Shale.

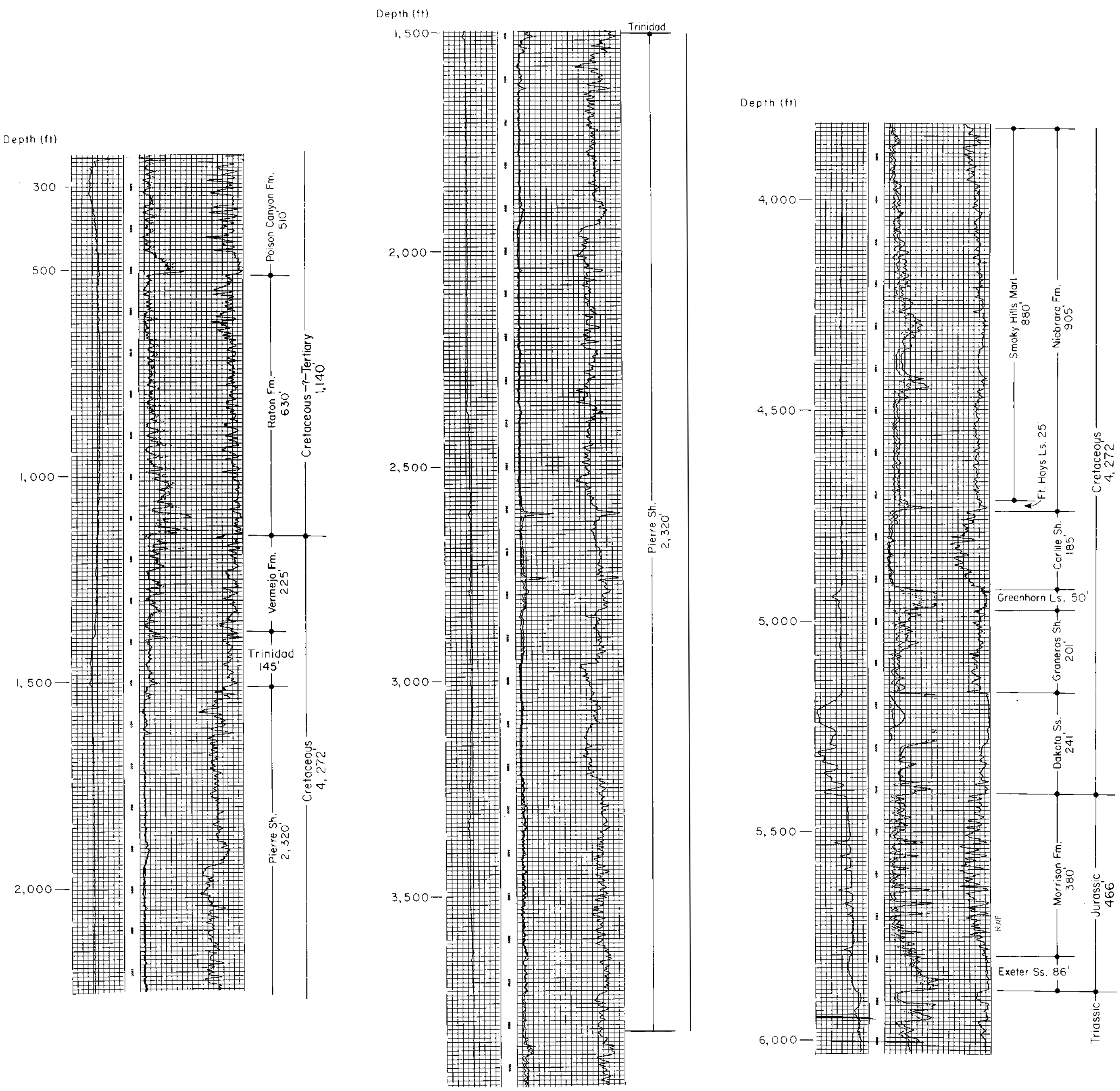
The Dakota Sandstone is about 250 ft thick in the vicinity of the eastern Valle Vidal Unit where it is comprised of porous sandstone interbedded with shale. Where traps exist, the Dakota might make an attractive reservoir target with the overlying Graneros Shale acting as source rock. The Dakota Sandstone has yielded numerous shows of oil and gas in Colfax County (Foster, 1966), but no commercial production. It is a produced water disposal zone at the Vermejo Park Ranch (Roy Johnson, NMOCD, 2004, pers. comm.).

The Graneros Shale is dark gray and contains thin beds of bentonite, limestone, and sandstone, whereas the Greenhorn is thin beds of limestone and interbedded calcareous to chalky shale (Baltz, 1965). Overlying the Greenhorn Limestone is the dark gray Carlile Shale, which is in turn overlain by the Niobrara Formation. The Niobrara Formation is comprised of the Fort Hays Limestone (lower part) and the chalky marls of the Smokey Hill Member. The mixed calcareous and clay-rich composition of the Niobrara Formation makes it a potential fractured reservoir as well as a potential source rock.

Above the Niobrara Formation is the 2000+ ft thick Pierre Shale. Most of the Pierre Shale is dark gray noncalcareous shale. The upper several hundred feet consist of gray, thin-bedded, fine grained sandstone intercalated with thin beds of dark gray silty and sandy shale, essentially distal intertongues with the overlying Trinidad Sandstone (Johnson et al., 1966). The Pierre is an oil- and gas-prone source rock and has yielded numerous shows in the Raton Basin. Figure 3.9 is a type electrical log that demonstrates the great thickness of the Pierre Shale relative to other Mesozoic Formations in the Raton Basin.

Trinidad Sandstone through Poison Canyon Formation (Cretaceous-Paleocene): This section is the most important relative to coalbed methane potential of the eastern Valle Vidal Unit. It contains coal beds that serve as source rocks. Reservoir rocks include coal and sandstone beds. The coal-bearing formations in the Raton Basin (Fig. 3.10) are underlain by the Trinidad Sandstone. As thick as 130 ft, it forms a prominent cliff along the eastern edge of the basin. Hills (1899) described the Trinidad Sandstone in the Raton Basin, later to be defined by Lee (1917). The base of the Trinidad can be difficult to pick in electric logs as there is a gradational contact between it and the underlying Pierre Shale. The upward-coarsening sandstones show bioturbation and commonly contain *Ophiomorpha* casts (Flores, 1987) suggesting a shallow marine to shoreface depositional environment. The lower part of the formation

Figure 3.9 Type electric log for the eastern Valle Vidal Unit from the Gourley #1 Vermejo Park well. The location of this well is problematic and is discussed in Section 4.1 of Chapter 4. Figure from Grant and Foster (1989).



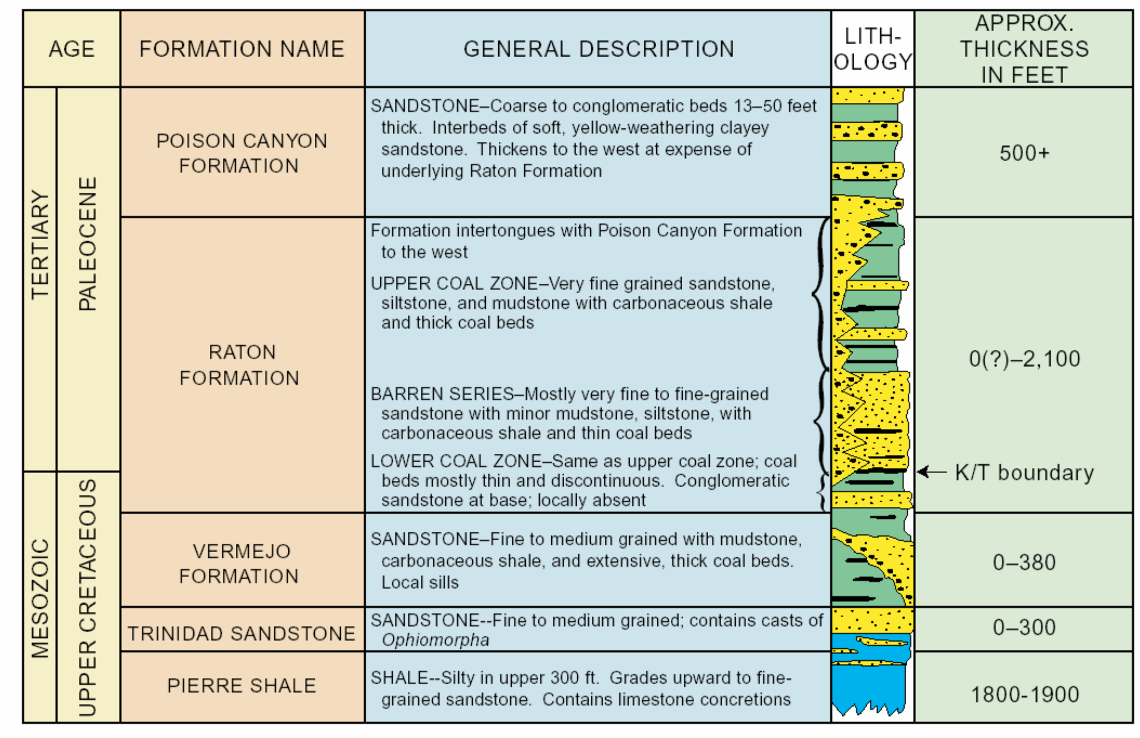


Figure 3.10 Generalized stratigraphic column for Cretaceous and Paleocene rocks in the Raton Basin. From Flores and Bader (1999), modified from Pillmore (1969), Pillmore and Flores (1987) and Flores (1987).

has ripple lamination that grades upward into planar and trough cross-lamination (Flores, 1987), demonstrating an upward increase in depositional energy and reflecting the overall shallowing and regression of the seaway.

Conformably overlying the Trinidad Sandstone is the coal-bearing Vermejo Formation. However, Lee (1917) and Wanek (1963) recognized transgressive tongues of the Trinidad Sandstone extending into the Vermejo Formation along the southern margin of the basin. Both noted the general thinning of the Vermejo Formation to the east. Lee (1917, p. 51) defined the Vermejo Formation for exposures at Vermejo Park, and described it as the "coal measures lying immediately above the Trinidad Sandstone." This sequence of sandstone, siltstone, mudstone, shale, carbonaceous shale, and coal averages approximately 350 ft thick. The Vermejo Formation represents delta-plain deposits landward of the shoreface delta-front and barrier-bar sediments of the Trinidad Sandstone (Flores, 1987; Pillmore and Flores, 1987). The thicker coals are commonly concentrated near the base of the Vermejo Formation in proximity to the Trinidad upper shoreface sandstone.

In general, the Raton Formation overlies the Vermejo Formation with an unconformable contact. Lee (1917) divided the Raton Formation into the informal basal conglomerate, lower coal zone, a sandstone-dominated barren series (middle barren sequence herein), and an upper coal zone. The Raton Formation basal conglomerate is a 10- to 30-ft-thick pebble conglomerate to granule quartzose sandstone eroded into the Vermejo Formation. Overlying the basal conglomerate, the 100- to 300-ft-thick lower coal zone consists of sandstone, siltstone, mudstone, carbonaceous shale, and thin, discontinuous coal. This sequence represents meandering stream floodplain deposits that grade upward into braided stream deposits of the overlying middle barren sequence (Flores and Pillmore, 1987; Johnson and Finn, 2001), which varies from 165 to 600 ft thick. The middle barren sequence merges with the Poison Canyon Formation to the west (Pillmore and Flores, 1987). The upper coal zone is a return to finer-grained deposits in an alluvial plain environment (Flores, 1987). Peat swamps developed between the meandering stream channels. Coal beds are lenticular within the upper coal zone but tend to have greater thickness than those in the lower coal zone of the Raton Formation.

The Raton Formation is overlain by and intertongues to the west with the Poison Canyon Formation; the contact can be gradational in parts of the basin. Where the contact intersects the surface, it is mapped as a transitional area (e.g. as mapped by the New Mexico Bureau of Geology and Mineral Resources and others). This is due in part to extensive vegetative cover, but also due to the lack of a detailed study of the Poison Canyon Formation. The Poison Canyon Formation consists of coarse grained to conglomeratic arkosic sandstones. This unit represents prograding conglomeratic lithofacies derived from the Sangre de Cristo uplift. As mentioned previously, this formation is the primary bedrock at the surface in the eastern Valle Vidal Unit.

Oligocene and younger igneous rocks: All of the stratigraphic units described above are intruded or domed by Oligocene or younger igneous intrusions somewhere within the region. These intrusions include dikes, sills and laccoliths. Miggins (2002) conducted an extensive study dating many of the igneous features of the region, reporting ages from 33 to 19.7 Ma. At least three oil and gas exploratory wells penetrated igneous rocks (rhyodacite) at shallow depths (less than 4000 ft) over the Vermejo Park dome. Other igneous intrusions in the region include sills in coal beds and dikes that penetrate the entire stratigraphic section. Rock samples from the Firewall dike in the eastern Valle Vidal Unit yielded an Oligocene age of 28.0±0.8 Ma (Million years before present) using the 40Ar/39Ar dating method (Geochronology Laboratory at the New Mexico Bureau of Geology and Mineral Resources, March 18, 2004, unpubl. report).